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Procedia Engineering 89 (2014) 53 – 58

Procedia Engineering

www.elsevier.com/locate/procedia

16th Conference on Water Distribution System Analysis, WDSA 2014

Hierarchical Decomposition of Water Distribution Systems for Background Leakage Assessment

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Abstract

This study applies hierarchical decomposition to solve the background leakage control-oriented optimal design problem for the C-Town distribution system. Specifically, the system is first divided into 33 clusters organized in a two level hierarchical structure. The clusters are further classified into trunk clusters and branch clusters respectively. Next, in a sequential manner based on the hierarchy, optimal pressure control strategies for each cluster is addressed with constraints on network performance imposed. As closure of pipes is allowed for leakage reduction, it is found that nearly all clusters are converted into tree networks with pressure control devices inserted.

Peer-review under responsibility of the Organizing Committee of WDSA 2014
Keywords:

1. Introduction

Leakage control in water distribution systems (WDSs), especially reducing background leakage given the difficulties in detection, is a crucial task for achieving sustainable urban water management due to water scarcity. Thereby, it is important to add leakage control as a key factor in optimal design and operational control of water distribution systems, i.e. to achieve the economic level of background leakage control (ELBLC). As there are both topological and behavioral complexities in WDSs, however, real-world WDSs commonly have a vast number of components with dynamic properties (the stochasticity of flow rates, pressures, and water demands etc) organized in intricate topologies (e.g. a combination of loops and branches). Consequently, it is usually rather difficult to identify the system's properties (e.g. the network structure, the operational scheme, and interactions between its components,

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Peer-review under responsibility of the Organizing Committee of WDSA 2014
doi:10.1016/j.proeng.2014.11.159

etc.). In search of solutions to this problem, one way is to simplify the network layout for visualization and data processing through clustering analysis. Clustering of networks consists of dividing a network into a number of sub-networks (i.e. clusters) with vertices and edges (Schaeffer, 2007). The resulting layout of clusters reveals the network structure and interactions between components more explicitly.

In the context of water distribution system analysis, there are a few studies exploring the application of clustering approaches. Bartolin et al. [1] applied the minimum spanning tree method to assist several model-based analyses of the Valencia water distribution system. The analyses involved network segmentation, detection of isolated parts of the network, isolation of broken pipes, and identification of the conveyance capacity of critical flow paths removal of which divides the network into two separated parts. Similarly, Tzatchkov [2] applied depth-first and breadth-first based graph algorithms to segmentation and water quality analysis of a large WDS. Specifically, as for the segmentation, the method proposed is able to identify independent networks and to detect errors in network data. As for water quality analysis, it speeds up the process of obtaining the contribution of multiple water sources to the consumption at nodes by mapping WDSs into directed graphs and making use of stacks for computation. Deuerlein [3] developed a generalized graph decomposition model that simplifies a network into a graph consisting of two main elements, called forests and cores, respectively. The model was subsequently applied to facilitate WDS analysis including, reliability analysis [4], model calibration [5], and the risk analysis of sensor placement [6]. Perelman and Ostfeld [7] developed topological clustering tools for analysis of flow patterns in WDSs. As clusters result from the flow directions in pipes, the placement of sensor can be proposed. Yazdani and Jeffrey [8] discussed the suitability of the clustering coefficient in graph theory as an indicator of path redundancy in WDSs. Regarding to leakage control, the most popular application of clustering analysis is to facilitate Districted Metered Areas (DMAs) planning. For instance, [9] and [10] presented spatial analysis tools for metered areas design in WDSs. Similarly, [11] designed two partitioning methods based on machine learning, with both graphical and vector information considered. More recently, Scibetta et al [12] and Diao et al [13] proposed complex network clustering techniques for the same task.

This study applies hierarchical clustering to background leakage control-oriented optimal design and control of the C-Town distribution system. By dividing the system into a bunch of clusters, the problem is explored in a subsystem by subsystem manner.

Nomenclature

WDS	water distribution system
ELBLC	economic level of background leakage control
PCV	pressure control valve

2. Methodology

Briefly, the cluster structure of the system is first detected. Next, in a sequential manner based on the hierarchy, optimal pressure control strategies for each cluster is addressed with constraints on network performance imposed, respectively. As closure of pipes is allowed for leakage reduction, it is found that all branch clusters and most of trunk clusters are converted into tree networks with pressure control devices at inlets. The flow chart of the whole process is plotted in Fig. 1.

2.1. Clustering

The system is divided into 33 clusters organized in a two level hierarchical structure (Fig. 2). The first level consists of 5 trunk clusters that are identical to the DMAs layout. The second level includes 28 branch cluster connected to corresponding trunk clusters.

2.2. Capacity optimization

At this step, capacity optimizations are carried out for trunk clusters and branch clusters respectively. As for trunk clusters, bottlenecks are identified and replaced with larger pipes in order to meet the minimum pressure requirement over the system. As for branch clusters, the task is to suppress redundancy by closing additional pipes. Specifically, with the pressure constraint imposed, all the possible combinations of pipe closure in each branch cluster are Fig.d out, and the best solution is regarded as the one with maximum number of pipe closure, and minimum leakage cost. As a result of this process, the topologies of all branch clusters are simplified to tree structures.

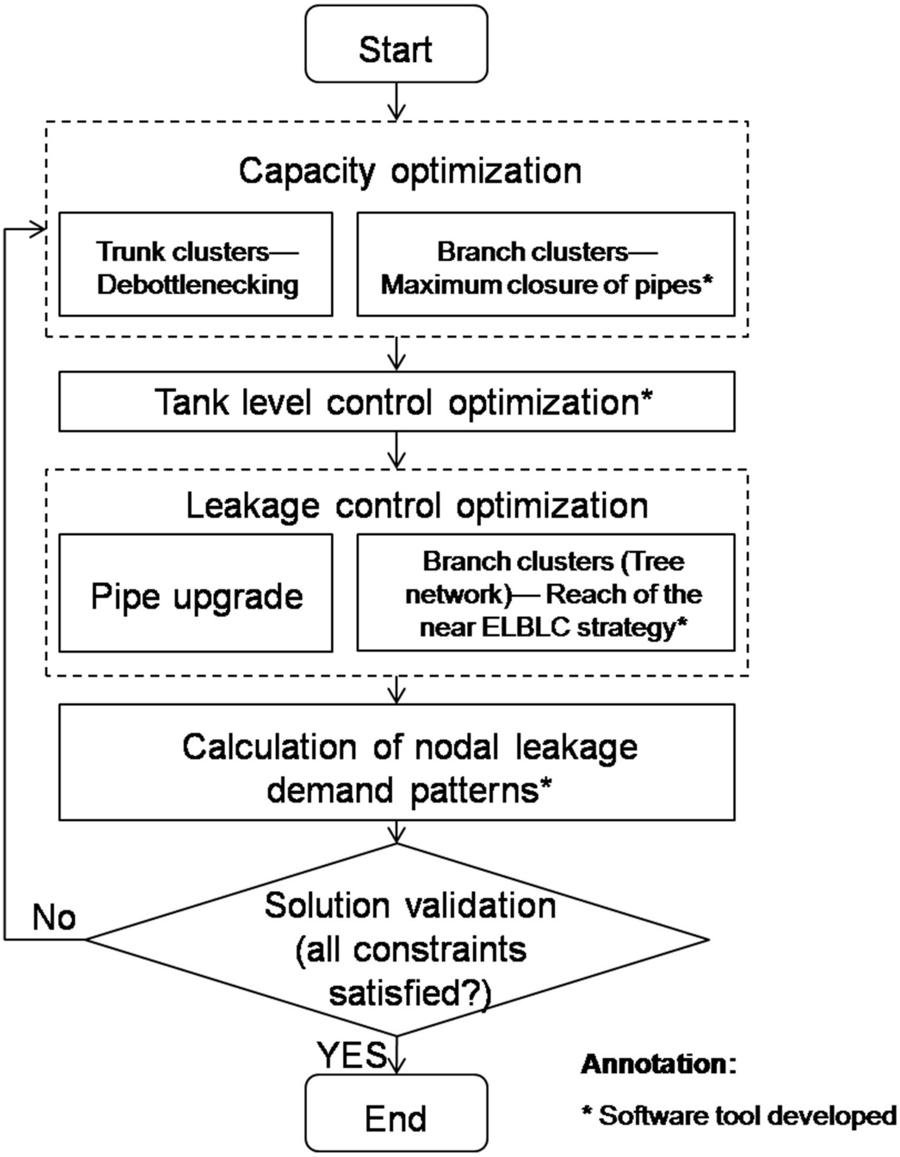

Fig. 1.Flow chart of the methodology

Fig. 2.Clustering of the C-Town network

2.3. Tank level control optimization

At this stage, the trigger tank level of each pump is optimized with minimization of the total cost on water loss and energy as the objective. Again, the optimization is carried out in a hierarchical manner. For this case, the DMAs are categorized into two levels as well (Fig. 3). Say, the trigger levels of pumps in DMA1 and the control valve V2 are first optimized. Next, the optimization process is operated for each one of the other level2 DMAs separately. Based on such a routine, the optimization is running iteratively until no significant improvement is achievable.

2.4. Leakage control optimization

In this study, pipe upgrading and pressure control are two main strategies considered for significant leakage reduction. In terms of pipe upgrading, it is found that replacements of many pipes (approx. 80%) could be beneficial for water loss saving. For the other pipes, more detailed cost effective analysis has to be done together with siting of pressure control valves (PCVs). In this regard, as each branch cluster is a tree network, the ELBLC of a branch cluster should be a theoretically deterministic value. Nevertheless, to identify the theoretical ELBLC by enumeration may still be too tedious to be feasible. Consequently, simplifications on the cost effective analysis for leakage reduction are made. Specifically, for each cluster the pipes undecided for upgrade or not are provided with a range of options (proper diameters) for replacement. Accordingly, all possible upgrading strategies or not upgrade are addressed. For each upgrading strategy, the cost-efficient PCV locations are determined. To do this, the network is divided into hierarchical organized control paths. As a next step, the cost efficiency of controlling each path is evaluated following an upstream-to-downstream manner. A PRV is installed if the water loss savings from pressure decreases at downstream nodes is higher than the PRV's cost. Based on the two processes above, the total costs of each upgrading strategy with PCV placed are compared and the solution with minimized total cost is selected.

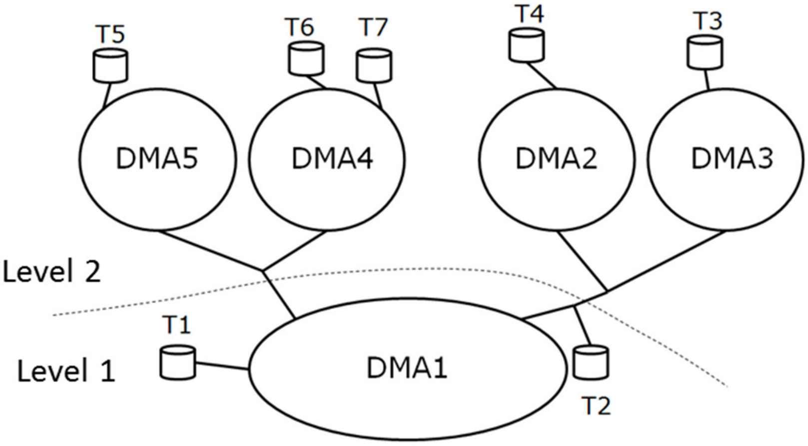

Fig. 3.The hierarchical structure of DMAs

2.5. Calculation of nodal leakage demand patterns

The demand patterns of nodal leakages are estimated by an iterative approach: 1) According to hydraulic simulation, calculate the nodal leakages at each time step using the proposed background leakage model; 2) Update nodal demands by adding nodal leaks as the secondary demand categories; 3) Re-run the simulation and re-calculate nodal leakages; 4) Compare the simulation results and calculated nodal leakage from step 1) and 2). The procedure is repeated until there are only negligible differences between the results. With nodal leakage included in the hydraulic model, the final solution for this study is validated to make sure all constraints are met.

3. Results and Discussions

With minimization of the total annual cost being the objective, reducing background leakage is found to be a dominating factor as the cost of water loss is tremendously high. To achieve substantial water loss reduction, 41 pipes are closed. On the one hand, fewer operating pipes result in lower leakage. On the other hand, highly simplified network structure could suppress redundancy and therefore facilitate leakage control via PCVs. Moreover, 349 pipes are upgraded to new ones, and 61 PCVs are installed. Although the total investment (approx. 0.72 million Euros) is considerable, it leads to approximately a 3.0 million reduction on the non-revenue water cost.

Regarding to the methodology, clustering of the system may enable doing analyses on a subsystem-by-subsystem manner. Although applying this method to optimization may not result in an overall global optimal solution, more detailed analysis could be implemented due to the reduced problem size and clues on understanding the system properties reveled by the division.

4. Conclusions

This study explores the application of clustering-based hierarchical decomposition to the background leakage control-oriented optimal design of C-Town distribution system.The system is decomposed into 5 trunk clusters and 28 branch clusters. Based on the cluster structure, all optimizations or analysis are undertaken cluster by cluster. For instance, each branch cluster is simplified into a tree structure by suppressing redundancy. Again, with topology simplified, it is able to identify the most cost effective PCV placement strategy and pipe upgrading options for each branch cluster. The final solution is to replace approx. 80% of the pipes in the system and locates 61 PCVs to dramatically reduce water loss cost, which is the biggest proportion of the total annual cost on the system.

Acknowledgements

The work reported is funded by the UK Engineering & Physical Sciences Research Council (EPSRC) project Safe &SuRe.

References

[1] Bartolin H., Martinez F., Cortes J. A. Topological Gis-based Analysis of a Water Distribution Network Model. Applications of the Minimum Spanning Tree. Computers and Control in the Water Industry (CCWI 2005), Exeter, UK, 2005.

[2] Tzatchkov V., Graph Algorithms For Connectivity Analysis Of Water Distribution Network Sectorization. 7th International Conference on Hydroinformatics, Nice, France, 2006.

[3] Deuerlein J. Decomposition Model of a General Water Supply Network Graph. Journal of Hydraulic Engineering, 134 (2008), 822-832.

[4] Deuerlein J. Efficient Supply Network Management Based on Linear Graph Theory. Water Distribution Systems Analysis Symposium, 2008, 1–18.

[5] Deuerlein J., Wolters A., Roetsch D., Simpson A., Reliability Analysis of Water Distribution Systems Using Graph Decomposition. World Environmental and Water Resources Congress, 2009, 1–11.

[6] Deuerlein J., Wolters A., Meyer-Harries L., Simpson A. Graph Decomposition in Risk Analysis and Sensor Placement for Water Distribution Network Security. Water Distribution Systems Analysis Congress, 2011, 394-411.

[7] Perelman L., Ostfeld A. Topological clustering for water distribution systems analysis. Environ. Modell. Softw., 26 (2011) 969–972.

[8] Yazdani A., Jeffrey P. Complex network analysis of water distribution systems. Chaos, 21 (2011) 016111–1–10.

[9] Sempewo J., Pathirana A., Vairavamoorthy K. Spatial Analysis Tool For Development Of Leakage Control Zones From The Analogy Of Distributed Computing, 10th Annual Water Distribution Systems Analysis Conference WDSA2008, Kruger National Park, South Africa, 2008.

[10]Di Nardo, A., Natale M. D.A Design Support Methodology for District Metering of Water Supply Networks. Water Distribution Systems Analysis 2010, Proceedings of the 12th International Conference, Tucson, Arizona, USA, 2010.

[11] Izquierdo J., Herrera M., Montalvo I., Perez R. Agent–based division of water distribution systems into district metered areas. 4th International Conference on Software and Data Technologies, Sofia, Bulgaria, 2009.

[12] Scibetta M., Boano F., Revelli R., Ridolfi L. Community detection as a tool for complex pipe network clustering. EPL, 103 (2013) 48001.

[13] Diao K., Zhou Y., Rauch W. Automated Creation of District Metered Area Boundaries in Water Distribution Systems. J. Water Resour. Plann.Manage., 139 (2013) 184-190.